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An Optimization Algorithm for Voltage Flicker Analysis

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Abstract

Maintenance of power quality standards is a critical issue in the electrical distribution networks today. Proper quality can be maintained only by continuously monitoring and analyzing the signals of interest so as to identify the sources of distortion. This paper presents an algorithm for analysis of voltage flickers in power signals, a common phenomenon in most of the networks involving heavy loads. The low frequency component responsible for modulating the power signal is extracted using an optimization algorithm. Further the algorithm separately identifies the signals affecting the fundamental component and the harmonics present in the power signal.

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Keywords: Flicker; low freqency; envelope; optimization.

1. Introduction

Power quality indicates the qualitative nature of power signal in terms of frequency, phase, amplitude and the harmonics present [1]. In the present day scenario, the load nature has changed significantly and hence maintenance of power quality requires better methods for their analysis and maintenance [2]. With the advent of smart grid networks there is the pressing need for maintenance of power quality throughout the network; and hence efficient analysis methodologies that can identify the exact reasons and suggest compensations for the same. A precise compensation for the disturbances can be introduced only by arriving at an estimate of the components involved after a detailed study of the distortions introduced. Voltage flickers are one of the very common power quality disturbances frequently observed in all networks, especially in networks involving heavy loads [3], [4].

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Flicker refers to the slow variations in voltage values of power signals over time. Such unexpected variations produces evident disturbances in the system and damages devices in the circuit. Flicker variations are typically reflected in the signal as a low frequency envelope modulating the power signal. Thus, the problem of flicker analysis can be considered as the study of this low frequency envelope to identify the source for this modulation. An algorithm that can effectively extract this low frequency modulating portion of the signal can facilitate the proper analysis of such voltage flickers.
Several such methods exist in literature, which vary by the methods they adopt for the distortion component estimation. One of the straight approaches to the problem is the use of Fourier transform to estimate the low frequency components present in the signal and thus identify the potential sources for the distortion. This method fails to deliver exact estimation owing to non-stationary nature of signal and leakage effects [5]. Several methods based on Hilbert transform [6] and wavelet transform [7] were also proposed for the analysis of these power quality disturbances. These spectrum based methods cannot provide high time and frequency resolution at the same time, and further are not capable of identifying the components with high resolution as is required for the exact analysis ofpower signals. [8] discusses a stochastic load flow analysis to be applied for analysis of power signals for heavy loads such as arc furnaces. This paper proposes an algorithm for flicker analysis via an optimization framework, which extracts the low frequency components modulating the fundamental component of the power signal as well as the harmonics present in the signal separately. Although the optimization framework would demand more computations as compared to the conventional methods, the method offers better results. The rest of this paper is organized as follows. Section II describes the optimization problem formulation and the Section III discusses the results obtained for the algorithm applied to a synthetic data set and finally the conclusion is drawn in Section IV.

2. Problem Description

Consider an appropriately sampled power signal $x \in R^N$ taken as $x = [x(0)\ x(1)\ ......x(N-1)]^T$ consisting offundamental frequency $f_0 \in R^+$ Hz and its harmonics. Here we consider x to be sum of two signals $x = v + w$, where $v \in R^n$ is the fundamental component modulated with a low frequency signal $u(n) \in R$ to simulate the effects of flicker distortions and is expressed as

$$v(n) = u(n)\cos\left(\frac{2\pi f_0 n}{f_s}\right), \tag{1}$$

$w \in R^N$ is the sum of harmonics of f_0 taken to be

$$w(n) = \sum_{i=1}^{K-1}\cos\left(\frac{2\pi k f_i n}{f_s}\right) \tag{2}$$

$n = [0,1,2,...,N-1] = Z_N$ and $f_s \in R^+$ is the sampling frequency. Our aim here is to extract the low frequency variations $u(n)$. As per the construction of the power signal described in (1) and (2) its original components arepure singletones of known frequencies, and hence the samples of the modulating component $u(n)$ can be considered as the time varying multipliers for the original singletonecomponents. Hence the signal x can be represented as

$$x(n) = \sum_{k=0}^{K-1} a(n,k)c(n,k) + b(n,k)s(n,k) \tag{3}$$

Where $c(n,k) = \cos(2\pi f_k n / f_s)$ and $s(n,k) = \sin(2\pi f_k n / f_s)$. This representation is quite similar to the decomposition of signals using K frequency bins as presented in [9]. An optimization frame work that could absorb the flicker variation and the original power signal variation into separate components using the model (3) is expressed as follows:

$$\min_{a,b} \sum_{k=o}^{K-1} \|Da_k\|_2^2 + \|Db_k\|_2^2$$
$$s.t.\ x(n) = \sum_{k=0}^{K-1} a(n,k)c(n,k) + b(n,k)s(n,k), \tag{4}$$

where $a, c, b, s \in R^{N\times K}$,

$$D = \begin{bmatrix} -1 & 1 & & & & \\ & & -1 & 1 & & \\ & & & \ddots & \ddots & \\ & & & & -1 & 1 \end{bmatrix}. \tag{5}$$

$D\,a_k$ and $D\,b_k$ represents the first order difference of a_k and b_k where $a_k, c_k, b_k, s_k \in R^N$ an $k \in [1, 2, ..., K-1] = Z_K$ .. The idea behind this formulation is very similar to the concepts presented in [9], but here the objective has been framed differently to achieve the optimization of interest. The formulation described in [9] minimizes sum of the ℓ_1 norm of $D\,a_k$ and $D\,b_k$ for all $k \in Z_k$. Such an optimization would drive a_k and b_k to be piecewise constant signals [9], as opposed to our present requirement of extracting smooth low frequency envelops and hence we minimize sum of the ℓ_2 norm of $D\,a_k$ and $D\,b_k$ for all $k \in Z_k$ .If the exact fundamental frequency f_0 is known, then c and s can be chosen properly so that a and b captures the flicker envelope.

3. Results and Discussions

For the purpose of analysis, a test signal of the form

$$x(n) = \left(\cos\left(\frac{2\pi f_{l0} n}{f_s}\right) + A_0\right)\cos\left(\frac{2\pi f_0 n}{f_s}\right) + \sum_{i=1}^{K-1}\cos\left(\frac{2\pi f_k n}{f_s}\right) \tag{6}$$

was generated as per the model described by (1) and (2s), where f_{l0} is the frequency of flicker component and $A_0 \in R$ is its corresponding DC shift. Such a signal of length $N = 1024$ taken at $f_s = 1024$ with $f_{l0} = 2$, $f_0 = 50$ Hz, $\{f_1, f_2, f_3\} = \{100, 150, 250\}$, $K = 4$ and $n \in Z_N$ is shown in Fig.1.

The flicker component $\cos\left(\frac{2\pi f_{l0} n}{f_s}\right)$ and the fundamental component $\cos\left(\frac{2\pi f_0 n}{f_s}\right)$ are separately shown in Fig.1 (a) and (b) respectively. The signal was subjected to algorithm (3) and corresponding results are shown in Fig. 2 which suggests that the algorithm could exactly capture the flicker variations as the vector a_0 .

The recovered components are shown in Fig. 3.Precise selection of frequency bins and the number of frequency bins is required for the good performance of the algorithm; in cases where the exact components of the original signal is unknown a reliable frequency estimation technique needs to be performed prior to analysis for deciding the frequency bins [10], [11], [12]. The algorithm was also found to be capable of removing different low frequency components affecting harmonics. This was tested on an input signal (different from (6)) of the form

Fig. 4(c) shows such a signal of length $N = 1024$ taken at $f_s = 1024$ with $f_{l0} = 2$, $f_{l1} = 1$,

$$x(n) = \left(\cos\left(\frac{2\pi f_{l0} n}{f_s}\right) + A_0\right)\cos\left(\frac{2\pi f_0 n}{f_s}\right) + \left(\cos\left(\frac{2\pi f_{l1} n}{f_s}\right) + A_1\right)\cos\left(\frac{2\pi f_1 n}{f_s}\right) + \sum_{i=2}^{K-1}\cos\left(\frac{2\pi f_k n}{f_s}\right) \qquad (7)$$

$\{f_0, f_1, f_2, f_3\} = \{50, 100, 150, 250\}$, $K = 4$. The flicker component $\cos\left(\frac{2\pi f_{l0} n}{f_s}\right)$ and $\cos\left(\frac{2\pi f_{l1} n}{f_s}\right)$ are separately shown in Fig.4 (a)and (b)respectively and $A_0, A_1 \in R$ are their corresponding DC shifts.

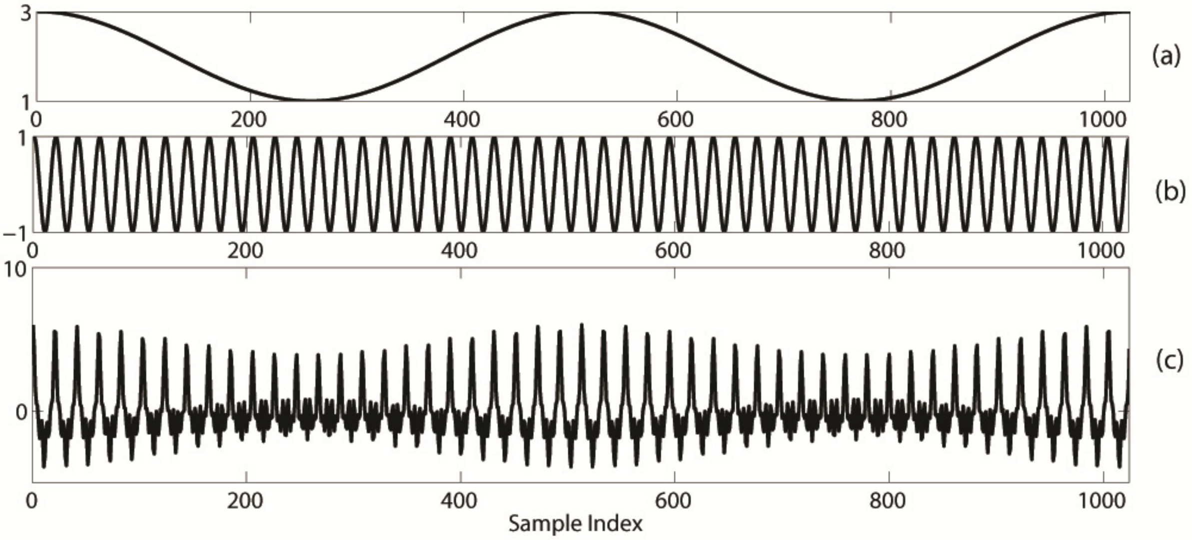

Fig.1.(a) Flicker component (b) Original power signal (c) Power signal with flicker.

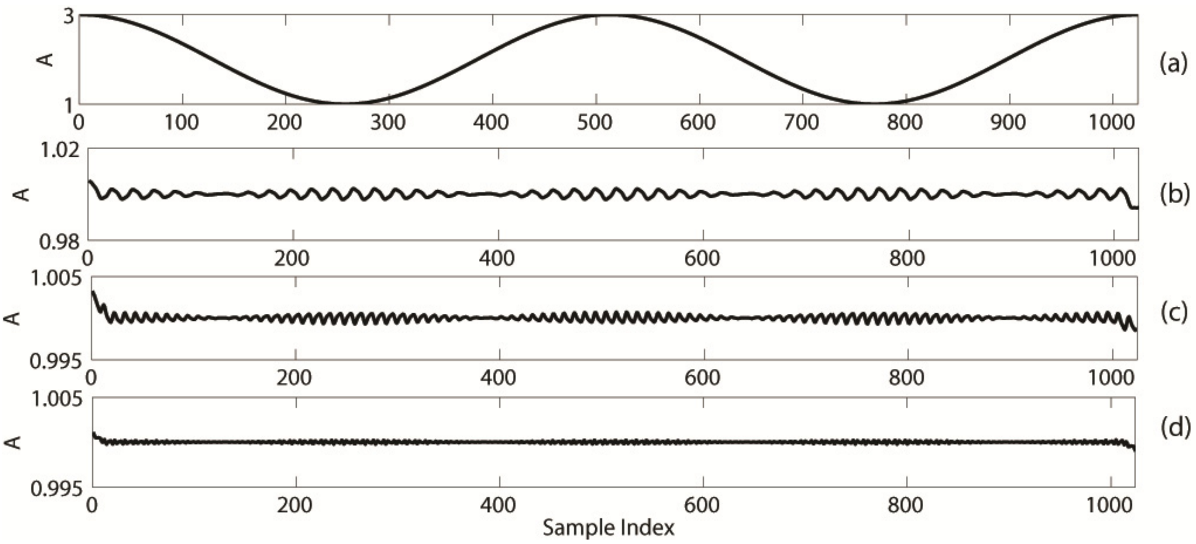

Fig. 2. Flicker components separated from (a) fundamental component (b) second harmonic (c) third harmonic (d) fifth harmonic

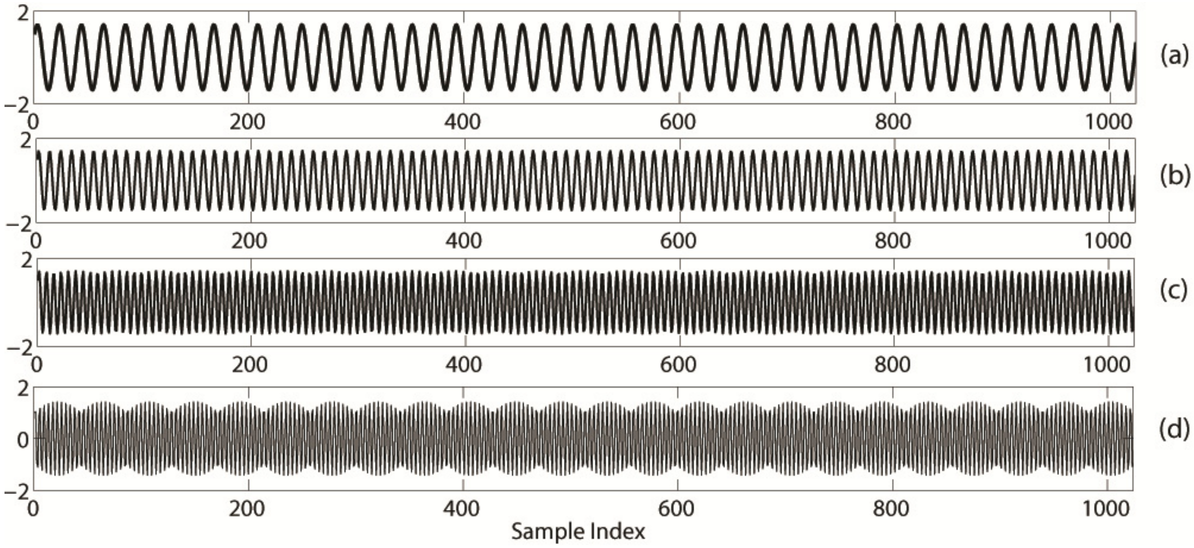

Fig. 3 Signal components separated from (a) fundamental component (b) second harmonic (c) third harmonic (d) fifth harmonic

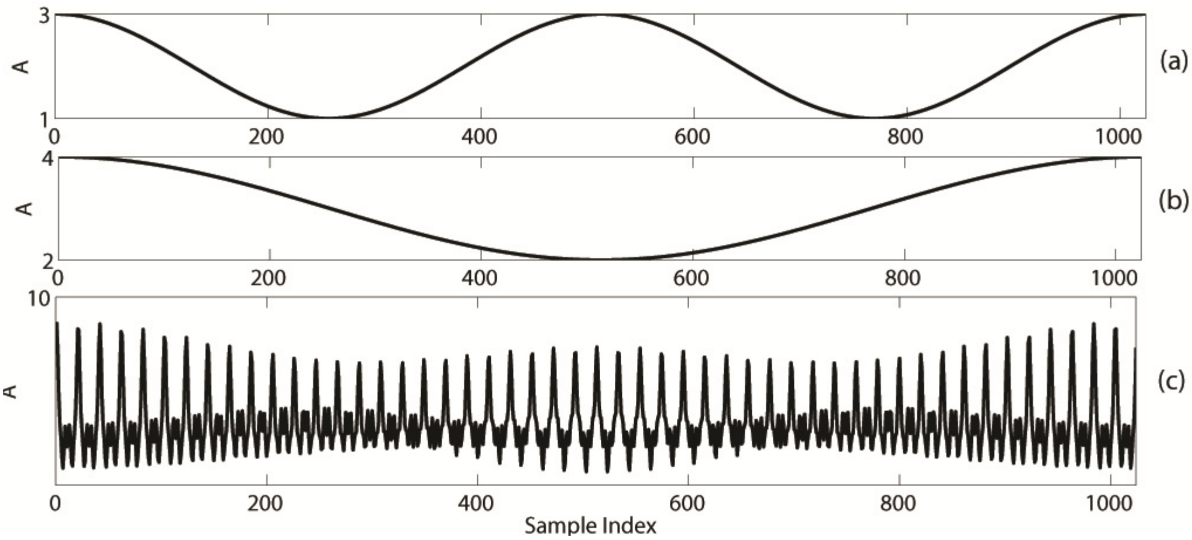

Fig. 4 Flicker component effecting the (a) fundamental component (b) second harmonic (c) Input signal

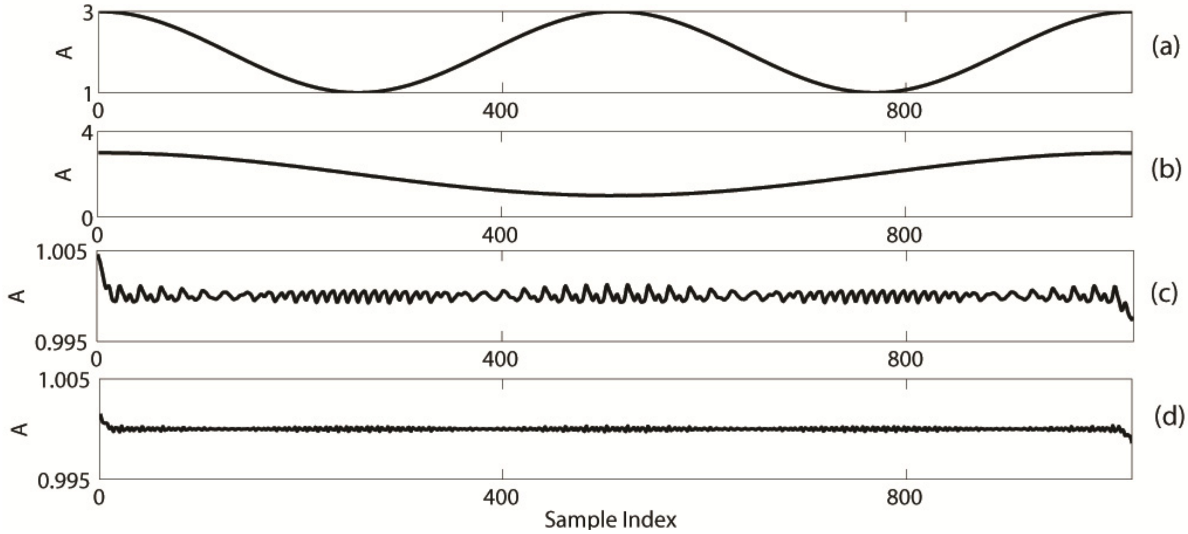

Fig. 5 Flicker component recovered from (a) fundamental component (b) second harmonic (c) Third harmonic (d) Fifth harmonic

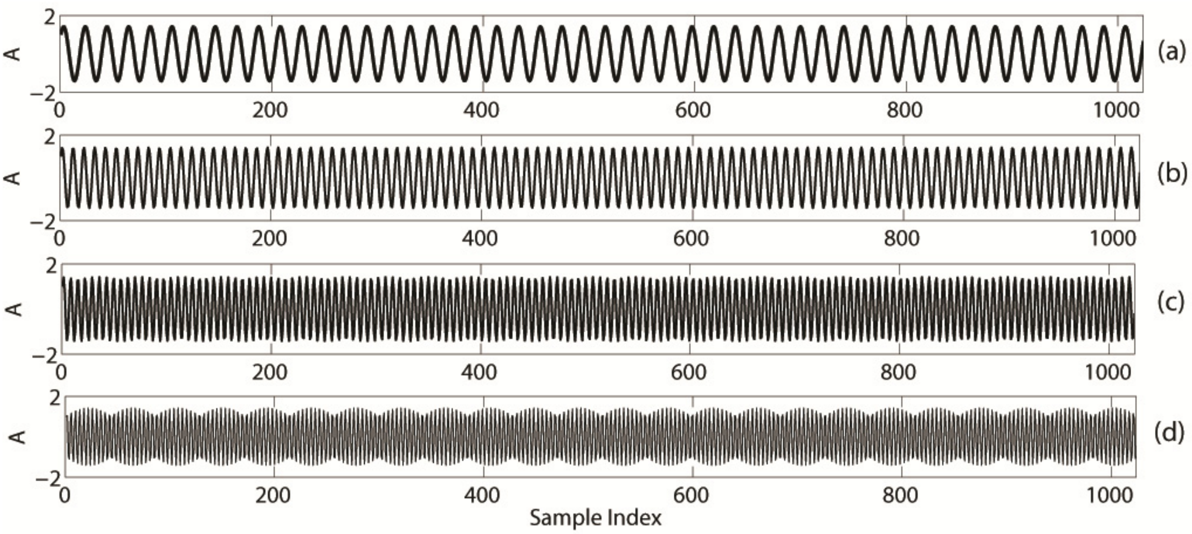

Fig. 6 Recovered signal components corresponding to (a) fundamental component (b) second harmonic (c) Third harmonic (d) Fifth harmonic

The result flicker components and signal components are shown in Fig. 5 and Fig. 6 respectively. The results shows that the algorithm was capable of identifying these close low frequency components affecting the harmonics.

4. Conclusion

The proposed algorithm is capable of effectively separating the low frequency flicker components modulating the power signals fundamental component and its harmonics. The flicker components effecting each harmonic is separately available such that with good frequency resolution techniques the exact frequency responsible for the flicker can be precisely determined thus facilitating detailed analysis and identification of their sources in the electrical power distribution networks..

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